A Plume Impingement Test for Code Validation

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Presented By
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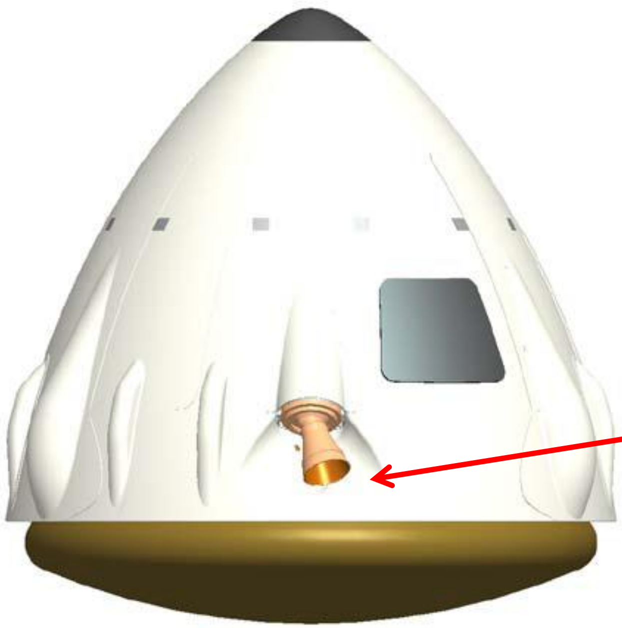
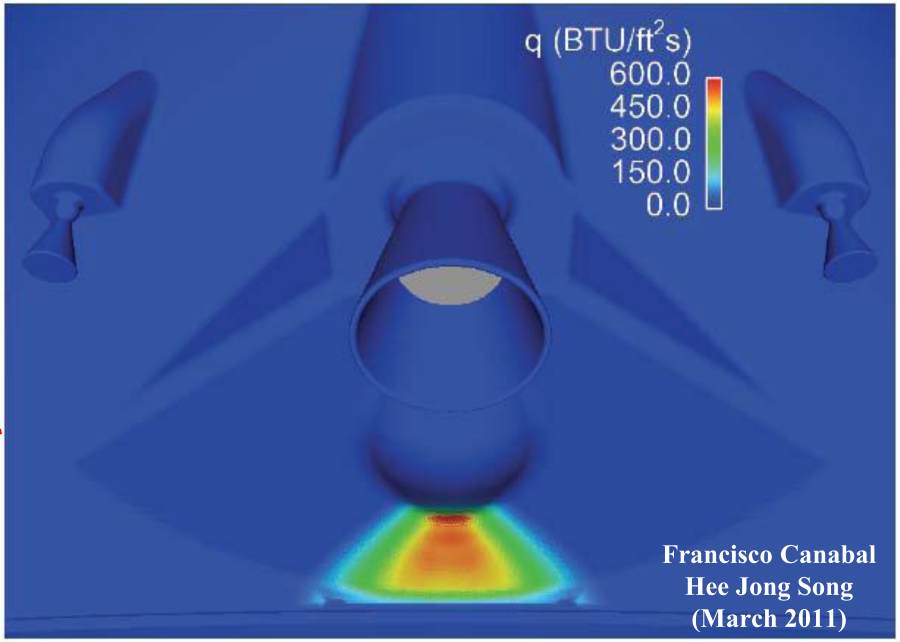
Outline

- Overview of Plume Impingement Test Panel (PITP)
  - Risk Mitigation Task
  - Mechanical Design
  - Instrumentation
  - Fabrication
- PITP Installation and Test at Marshall Space Flight Center (MSFC) Solid Propulsion Test Area (SPTA)
- Solid Rocket Test Motor N2 (SRTMV-N2) PITP Test Data Assessment Status
  - Pressure Data
  - Thermal Data
  - TPS Recession
- SRTMV-N2 PITP Data Analysis, Documentation, and Computational Fluid Dynamics (CFD) Code Validation Plans

Overview of PITP Risk Mitigation Task, Mechanical Design, Instrumentation, and Fabrication

Motivation for Risk Mitigation Proposal





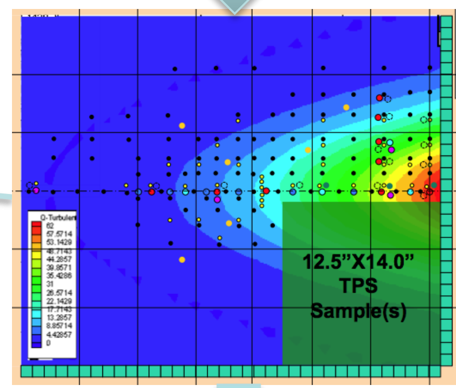
Risk Statements for Max Launch Abort System (MLAS) II (From 2/4/11):

- AERO-1: Given uncertainties associated with CFD modeling of hot plume exhaust products, there is a risk that the accuracy of the aerodynamics database could be reduced. (AERO)

- AERO-2: Given hot exhaust jet impingement from the AM exhaust…onto the surface of the fairing, there is a potential for hot plume impingement on the structure. (THERMAL)

Impact of SRTMV-N2 Plume Impingement Panel Test

LAS Risk Mitigation Project (NESC)



Unique Plume Impingement Database (public)

Commercial Crew Partner Benefits

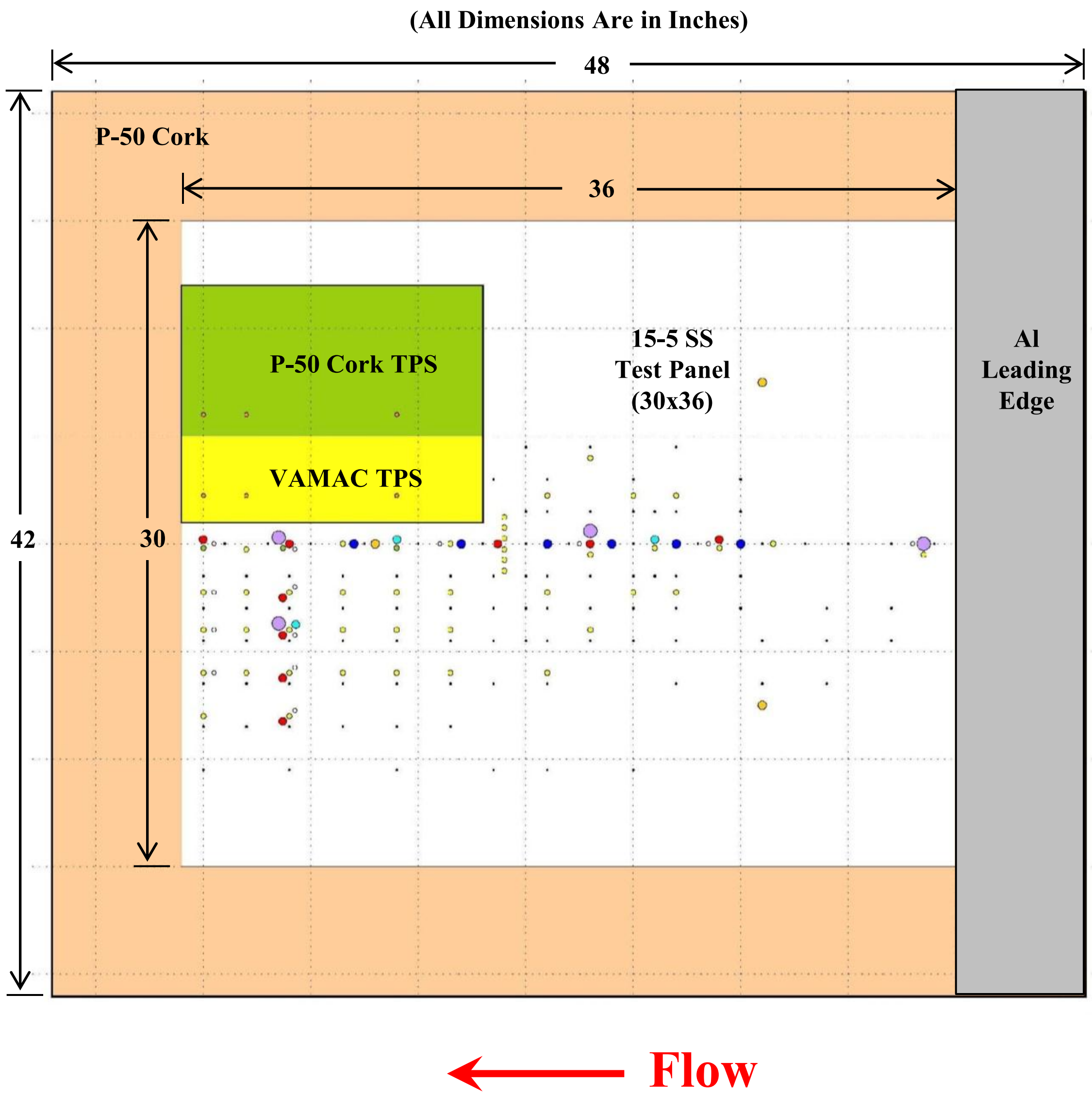
TPS Risk Mitigation for MPCV (recession rates)

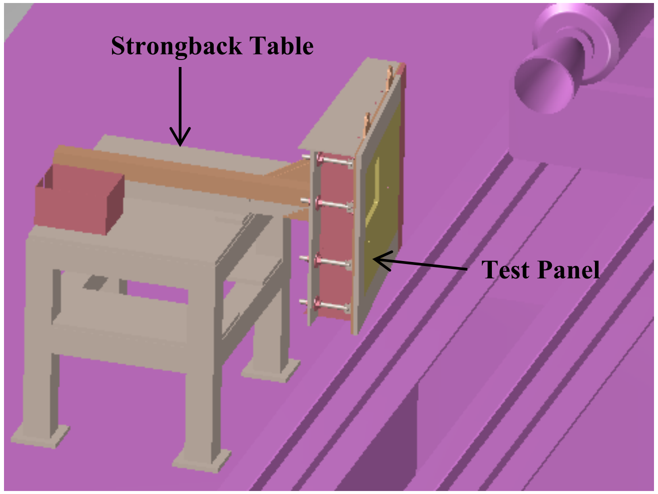
Abort Motor Environment Characterization

Validation Data for Multiple CFD Codes

- USM3D
- LOCI-CHEM
- DPLR
- Analytical Methods
- …

Design of the SRTMV-N2 Plume Impingement Test Panel





- Radiometer (4)
- Kulite (6)
- Accelerometer (3)
- Schmidt–Boelter Heat Flux (3)
- Gardon Heat Flux (9)
- Coaxial Tri–Thermocouple (3)
- Coaxial Thermocouple (43)
- Backside Thermocouple (13)
- Static Pressure (96)
- TPS Type–K TC (12)

Instrument Naming Convention

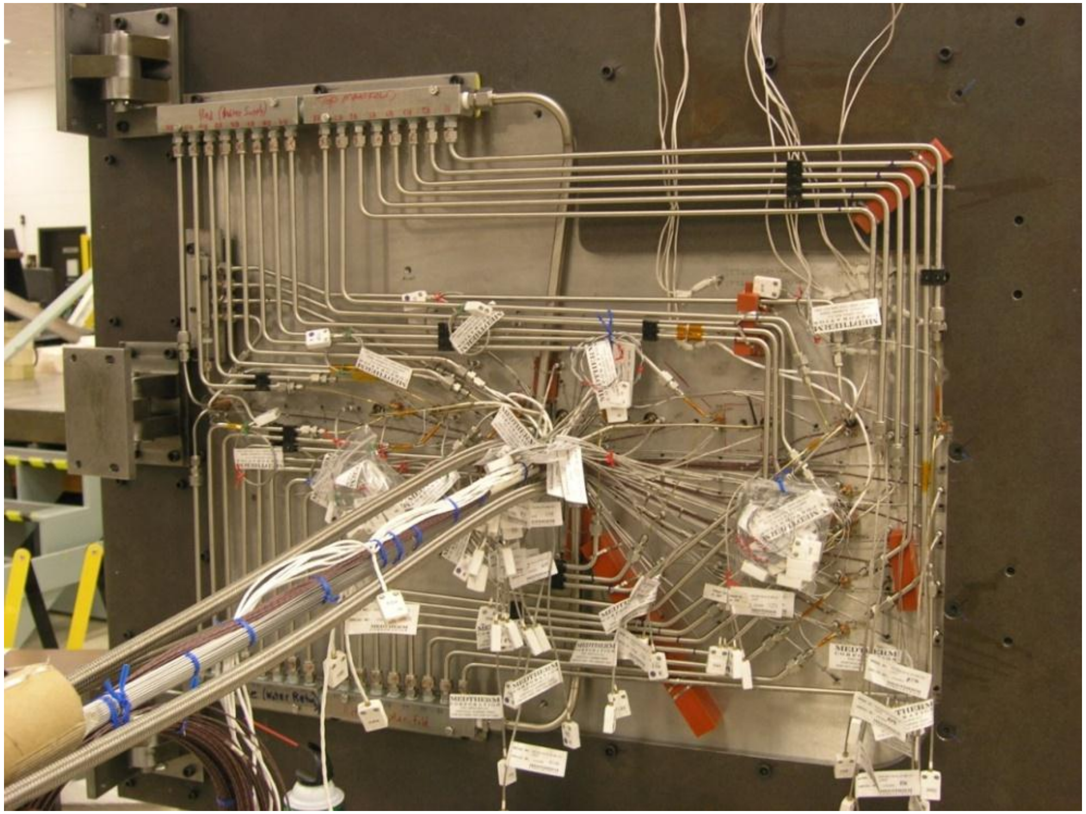
Naming Convention
iLLXX(p/n)YYdZ
i=Leading character ("i") to denote impingement plate instrument
LL=Abbreviation of Instrument type (see Below)
XX=Approximate X position in inches
(p/n)= Positive or negative associated with YY
YY=Approximate Y position in inches
dZ=Nondimensional depth, 0=surface, 5=backwall, if not specified use d0

Depth	
d0	Surface/Tri-Coax 1 (default)
d1	Tri-Coax 2
d2	Tri-Coax 3
d3	TPS 1
d4	TPS 2
d5	Backwall

Abbreviation	
SP	Static Pressure Tap
UP	Kulite (Unsteady Pressure)
CQ	Coaxial Thermocouple
GQ	Gardon Heat Flux Gage
RQ	Radiometer
AN	Accelerometer (Normal)
AT	Accelerometer (Tangential)
CT	Coaxial Tri-Thermocouple
SQ	Schmidt-Boelter Heat Flux
BT	Backside Thermocouple
TT	TPS Type K Thermocouple

Tri-coaxial Thermocouple Naming Convention (EXAMPLE: iCT35n00d2)	
i	Panel Test Instrument
CT	Tri-coaxial Thermocouple
35	approximate downstream distance from the panel leading edge (inches)
n	Below (not on) the centerline
00	approximate spanwise distance from the panel centerline (0 - 0.5 inches)
d2	0.060" below the surface

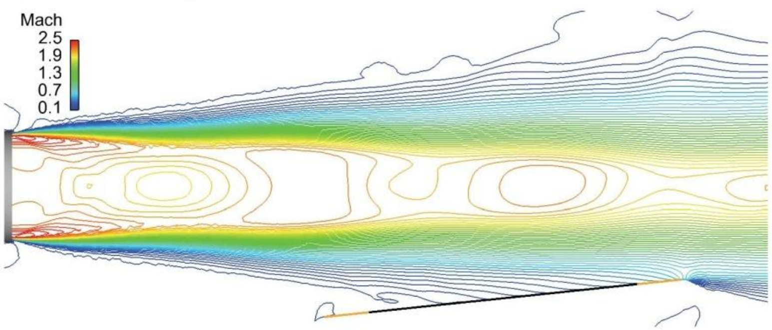
PITP Instrumentation Photos



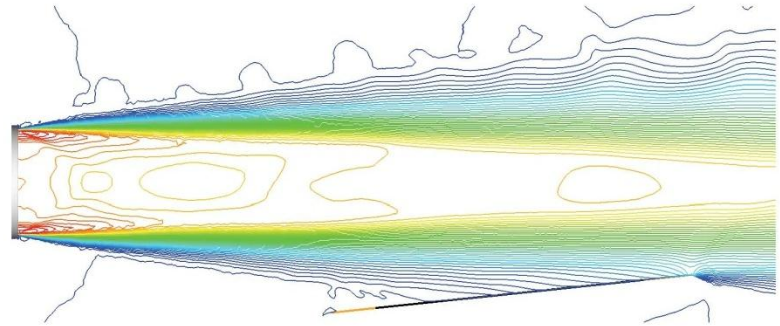
Loci-CHEM Pre-Test Predictions

Plume Distributions

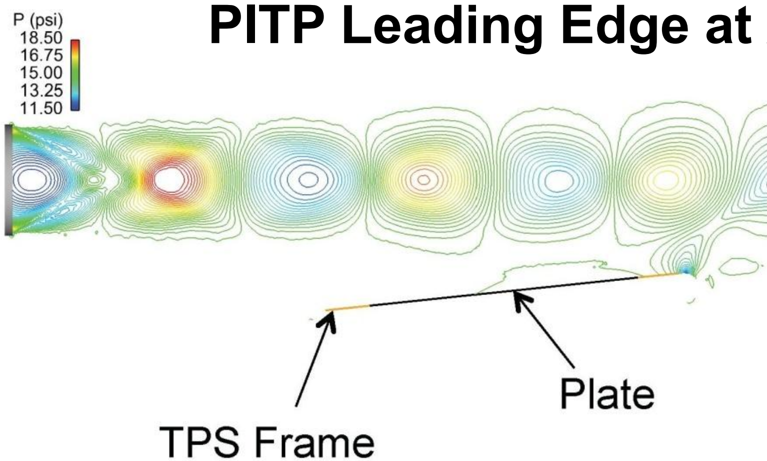
Gas Only

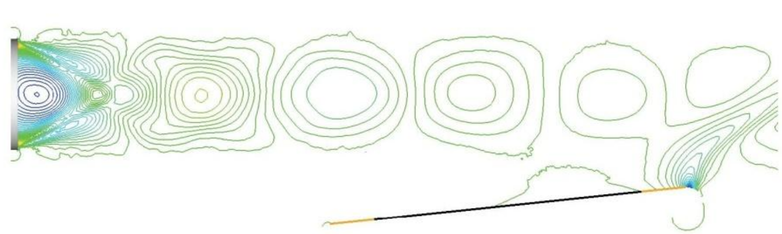


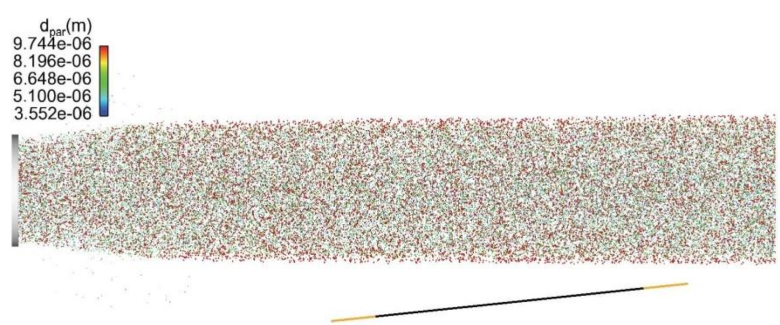
Gas + Particles



PITP Leading Edge at X=47.75", Y=16.8"; Angle=6°







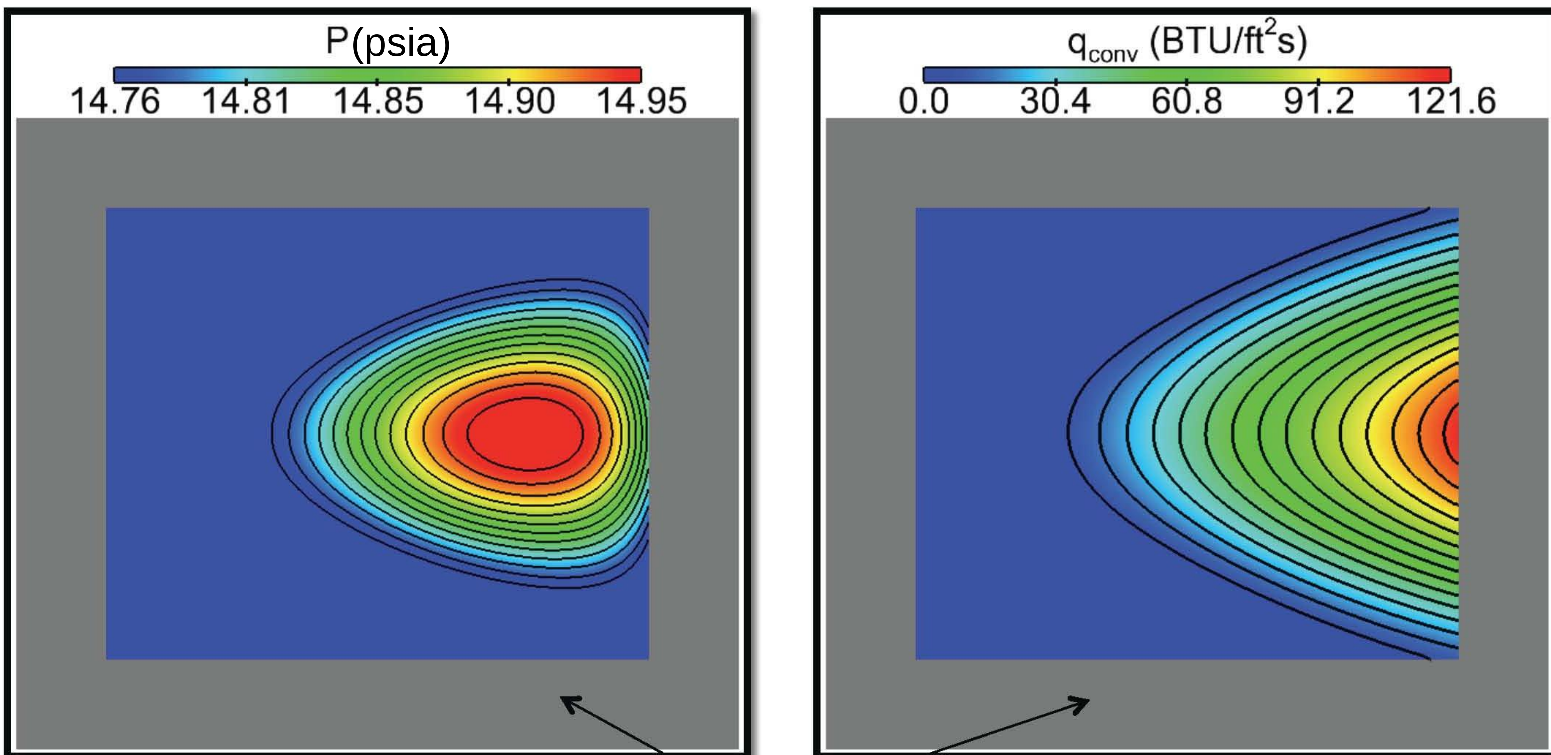
CFD Analysis:
Francisco Canabal – MSFC EV33

Pre-Test Loci-CHEM Predictions

Plate Surface Pressure and Convective Heat Flux Distributions

Loci-CHEM (gas + particles)

Flow Direction

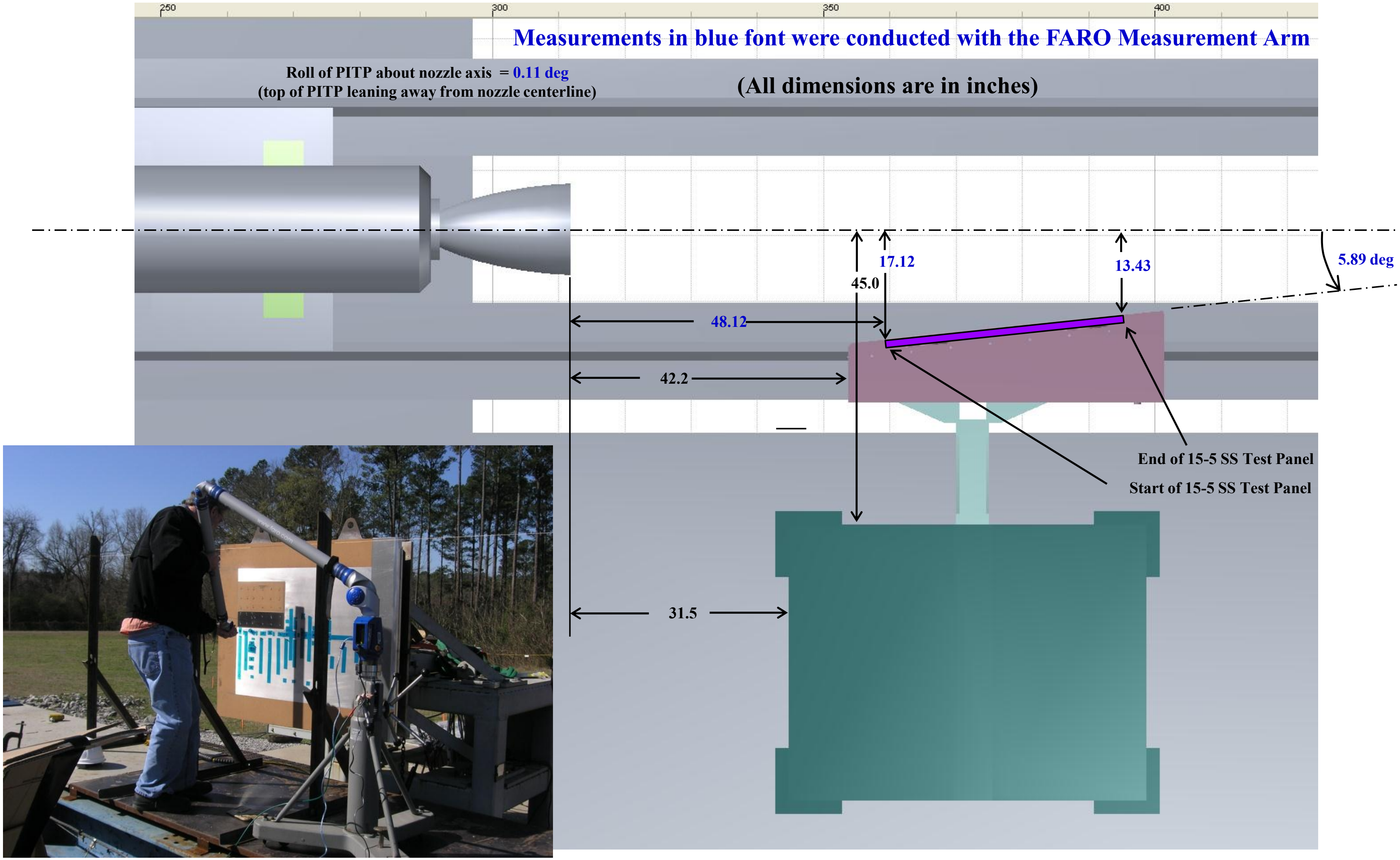


TPS

PITP Leading Edge at X=47.75", Y=16.8"Angle=6°

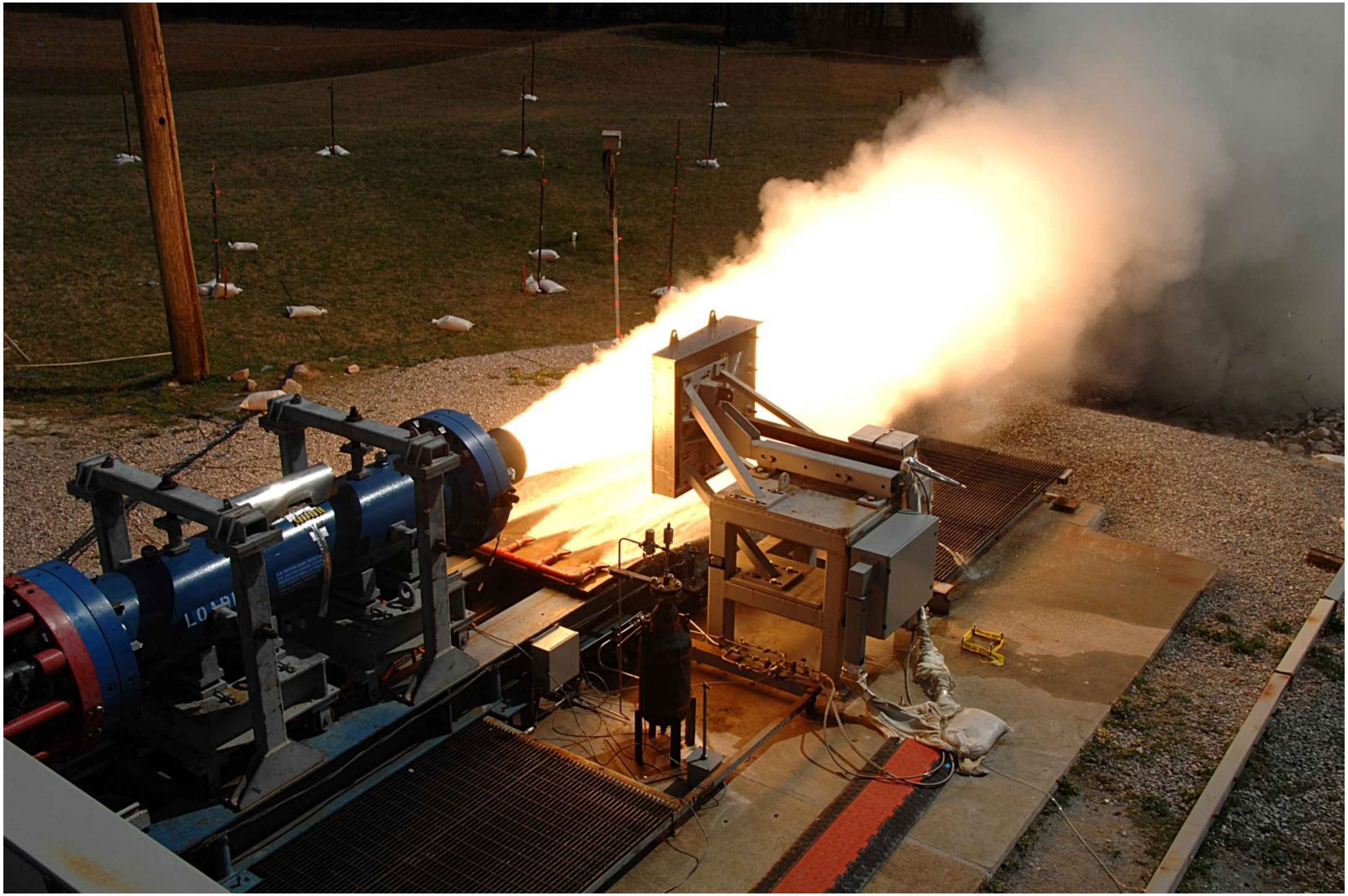
PITP Installation and Test at MSFC SPTA

PITP Position (Planform View)

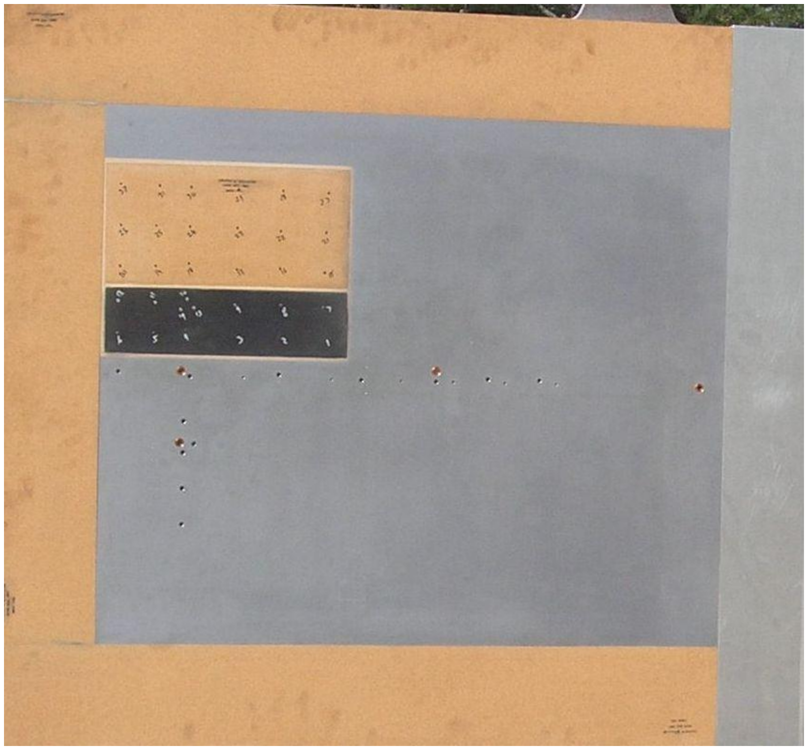


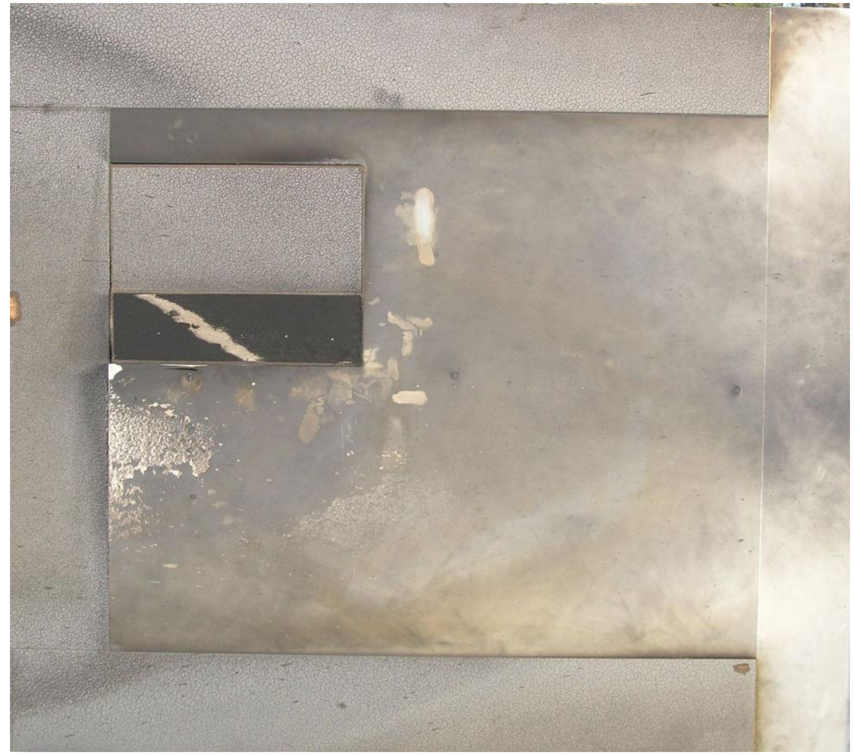
SRTMV-N2 PITP Test Video

CLICK PICTURE TO START VIDEO



Test Panel – Before and After



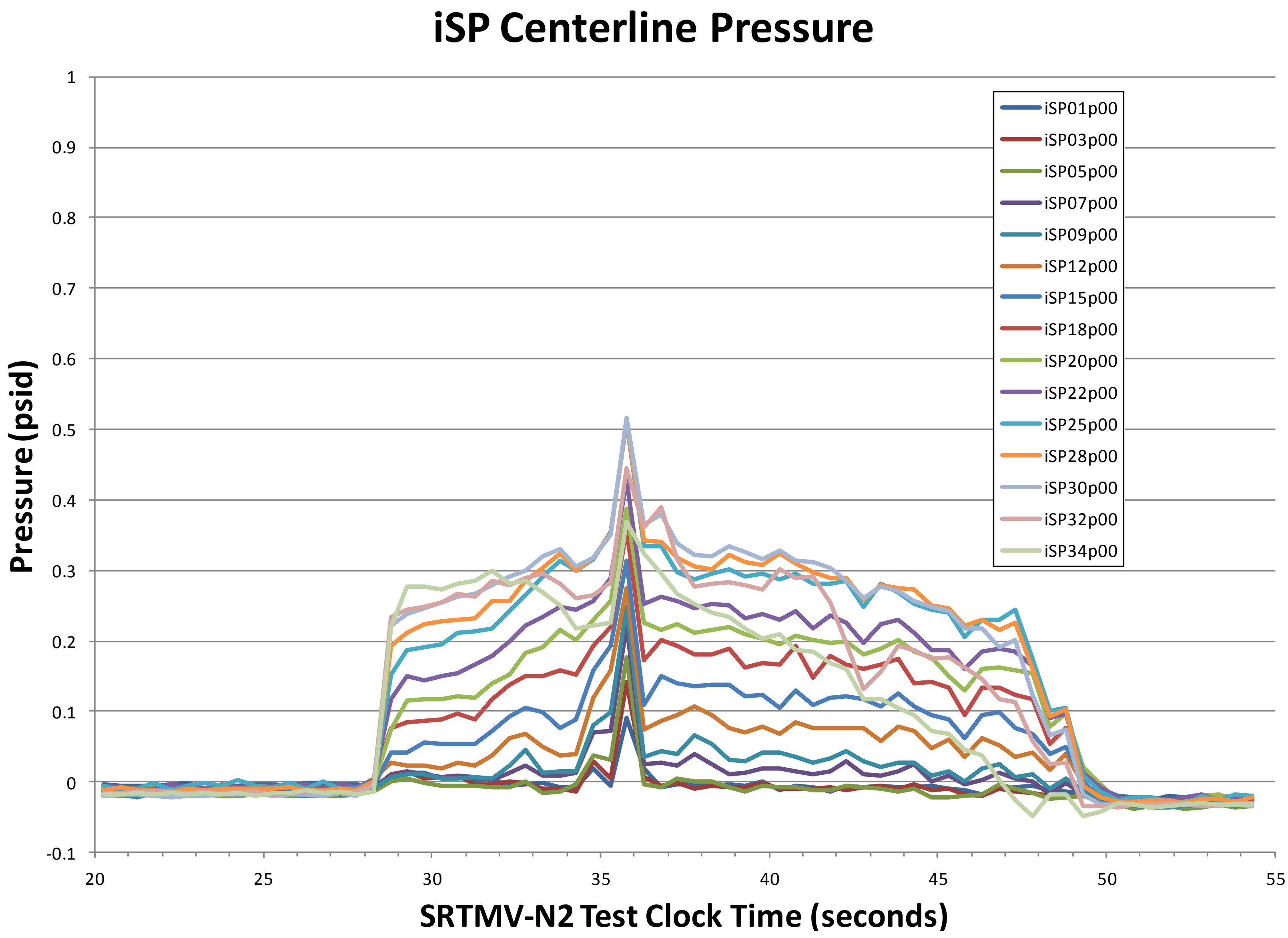


Post-test examination of the panel revealed significant recession of both the P-50 cork and VAMAC thermal protection materials. Aluminum deposition occurred below the plate centerline near the back end of the panel.

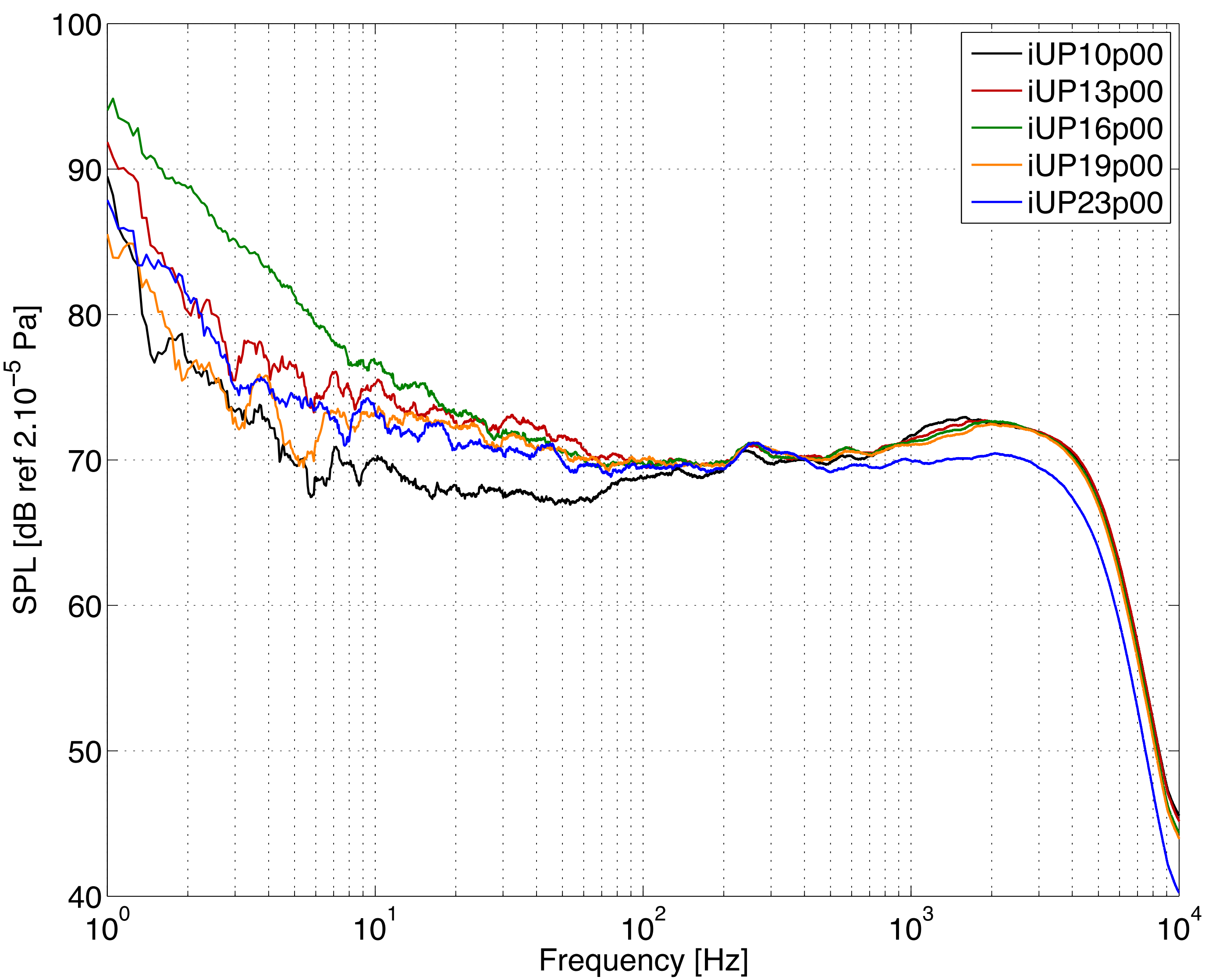
SRTMV-N2 PITP Test

Preliminary Pressure Data Assessment

Centerline Pressure Data



SRTMV-N2 PITP Unsteady Pressure



SRTMV-N2 PITP Test Preliminary Thermal Data Assessment

Thermal Analysis Overview

	INSTRUMENT SUITE				
Analytical Methods	**Coaxial Thermocouples** 	**Tri-Coaxial Thermocouples** 	**Gardon & Schmidt-Boelter Heat** 	**Radiometers** 	**Back wall thermocouples** 
SINDA	Temperature boundary condition	Temperature boundary condition	Heat Flux boundary condition	Heat Flux boundary condition	✓
Cook's Method	Temperature Boundary condition	Temperature Boundary condition	✓	✓	
Heat Conduction Equation		Temperature gradient	✓	✓	
Semi-Infinite Wall Solution			Heat Flux boundary condition	Heat Flux boundary condition	
Lump Capacitance Model	Initial and final temperature conditions	Initial and final temperature conditions	✓	✓	Initial and final temperature conditions

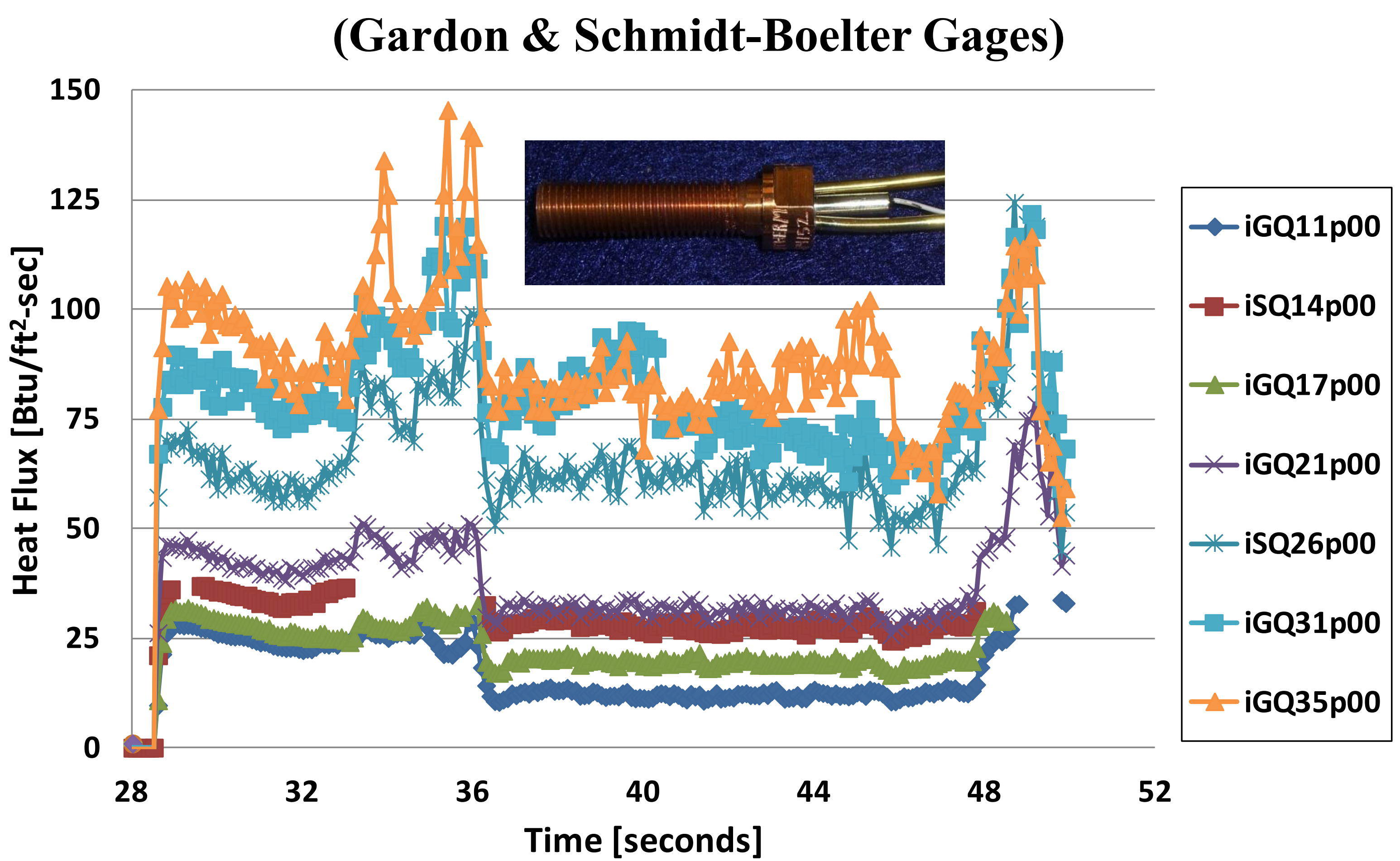
✓ **indicates that the measurement is not required as part of the analytical solution, but can be compared to the analytical result**

Types of Heat Flux Measurements

- **Direct Measurements**
  - Gardon Gages (9 instruments)
  - Schmidt-Boelter Gages (3 instruments)
  - Radiometers (4 instruments)

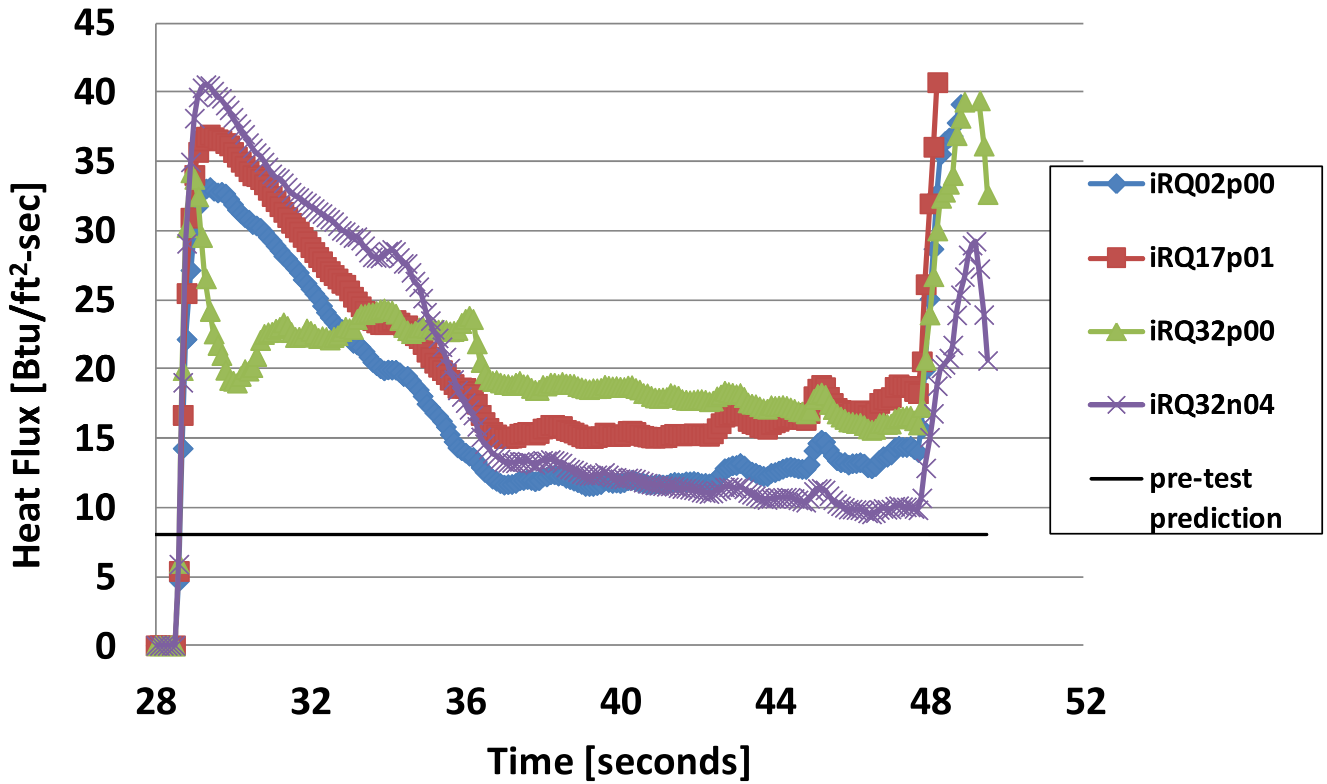
- **Indirect Measurement**
  - Heat Conduction via tri-coaxial thermocouple probe (3 instruments)
  - Analytical method using surface coaxial thermocouple measurements (43 instruments)

Centerline Heat Flux



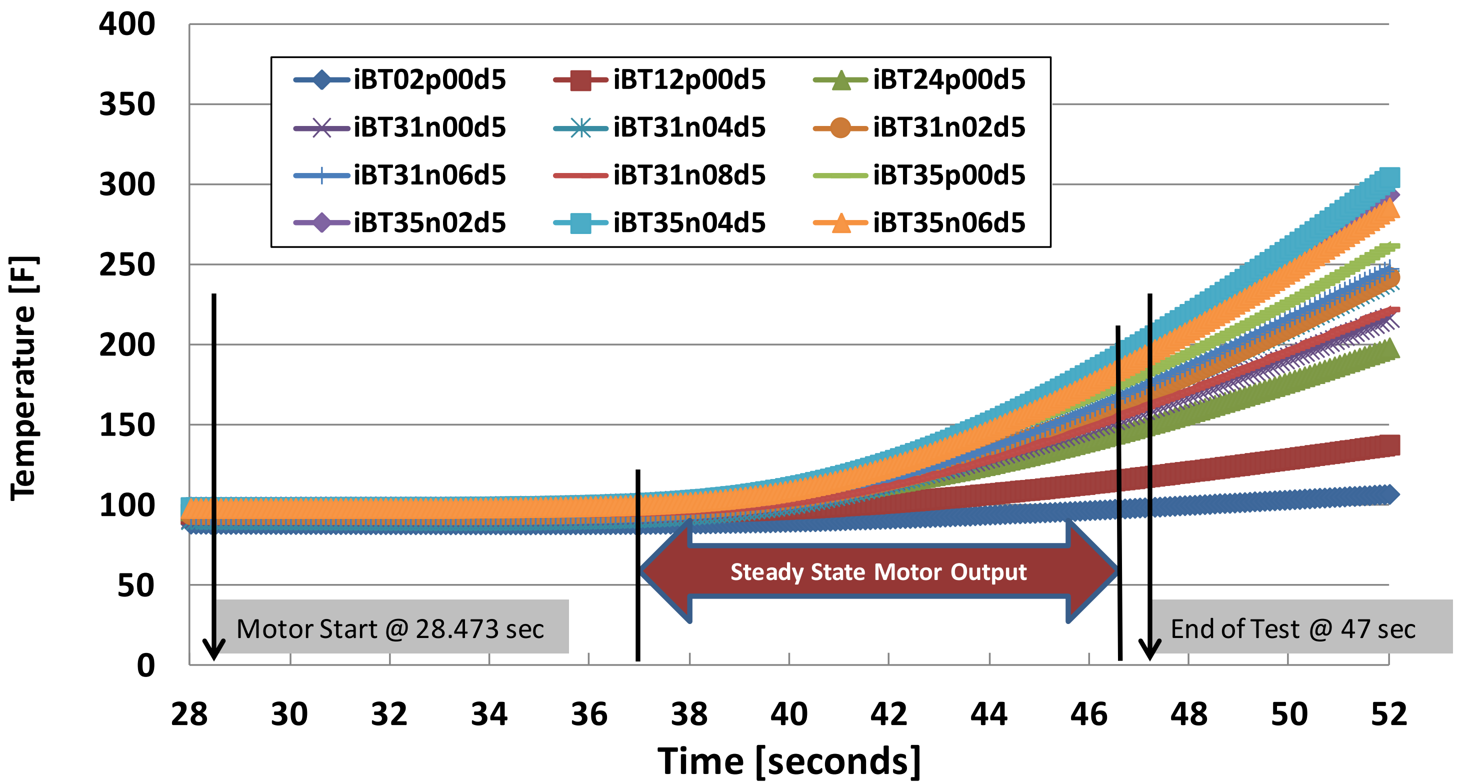
Due to the position of the plate, higher heat fluxes were predicted for the rear portion of the plate. Measurements agreed with predictions.
(Schmidt-Boelter gage (Station 14) provided an unexpected elevated reading)

Radiometers



Radiometers over-ranged at both the start and the end of the test (design limit set to 30 Btu/ft^2-sec).

Panel Back Wall Temperatures

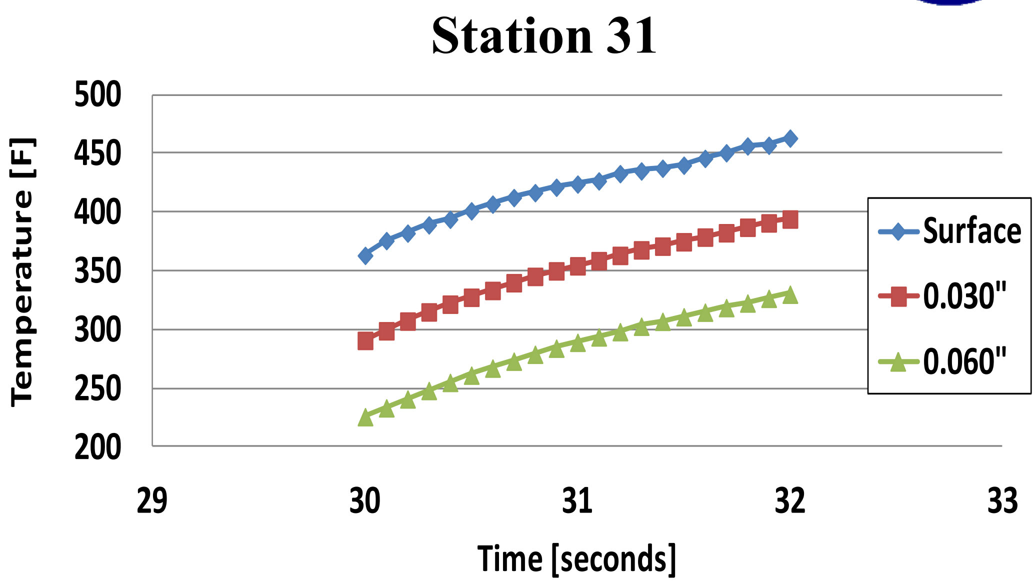


Back wall temperatures measurements do not respond appreciably until near the end of the motor burn.

Tri-coaxial Thermocouples

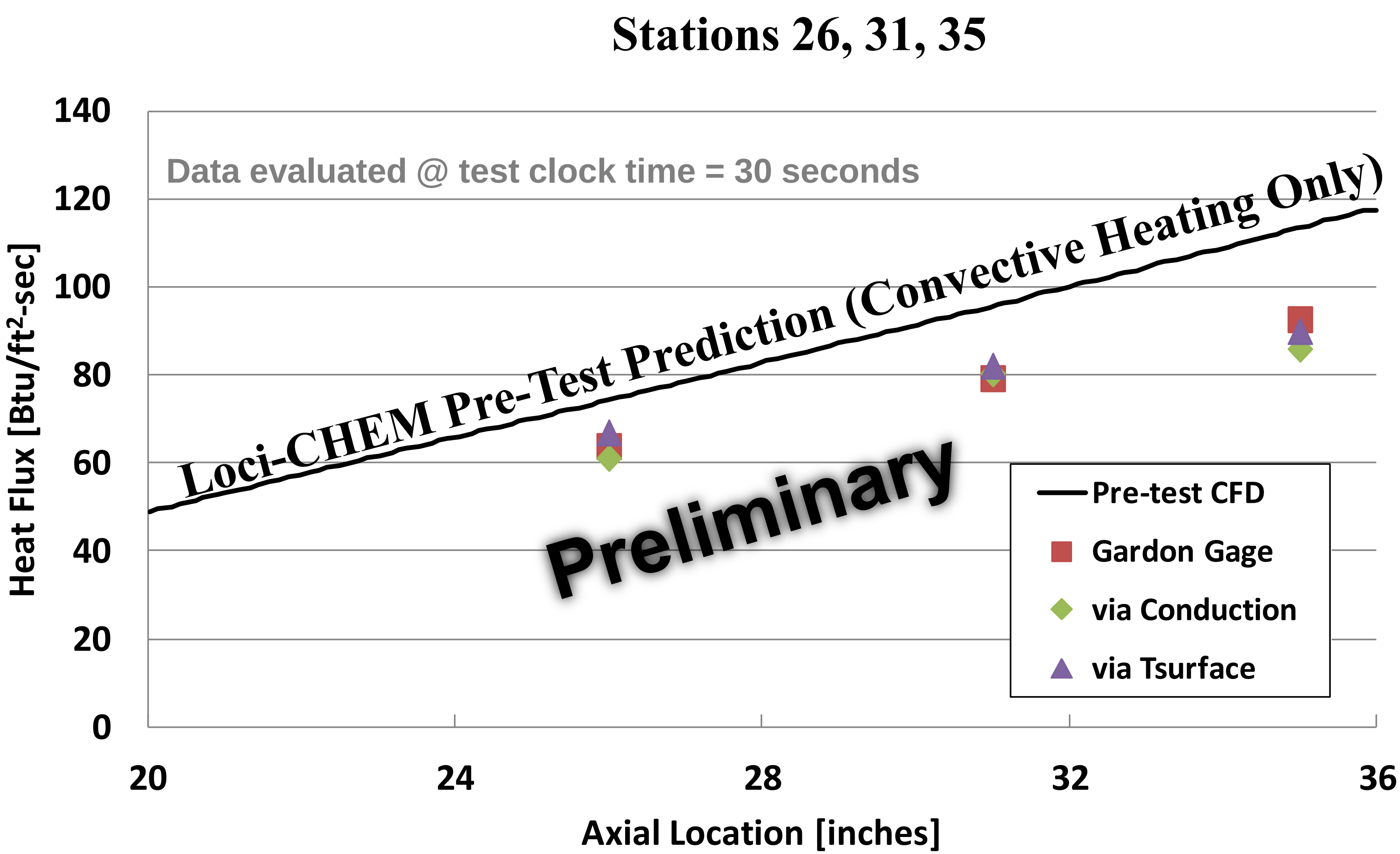
Tri-coaxial thermocouples measured material temperature at three different depths (0, 30, & 60 mils) and indicated that a well behaved thermal gradient was established through the material.

Heat conduction estimates for the tri-coaxial thermocouples matched heat flux gage measurements.



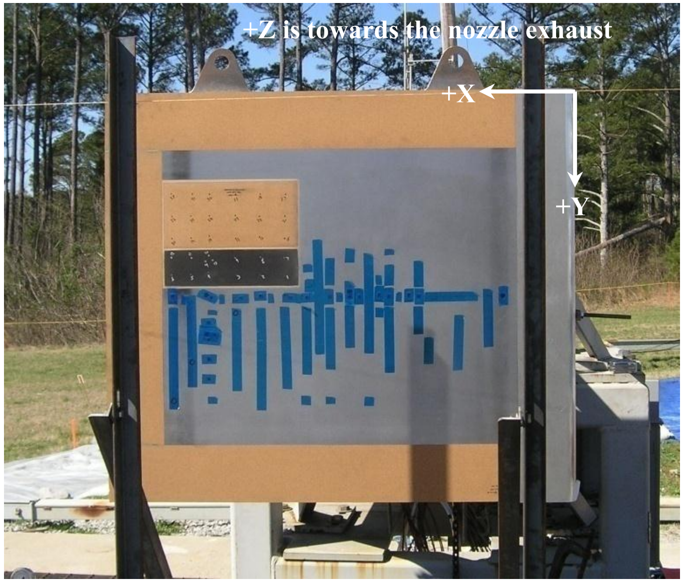
Time	Surface	30_mils	60_mils		Delta1	Delta2	DeltaT
30.0	362.8	290.4	225.3		72.4	65.1	137.5
30.2	382.0	306.9	240.6		75.1	66.3	141.4
30.4	392.9	321.6	254.7		71.3	66.9	138.2
30.6	406.5	333.1	267.2		73.4	65.9	139.3
30.8	417.1	345.4	278.8		71.7	66.6	138.3
31.0	422.9	354.4	289.0		68.5	65.4	133.9
31.2	435.7	363.0	298.3		72.7	64.7	137.4
31.4	438.7	371.5	307.1		67.2	64.4	131.6
31.6	446.9	379.1	315.1		67.8	64.0	131.8
31.8	455.0	387.2	322.5		67.8	64.7	132.5
			DT	R	70.8	65.4	136.2
			Dx	ft	0.0025	0.0025	0.005
			k	Btu/sec-ft-R	0.002873	0.002873	0.002873
			q	BTU/ft^2-sec	81.35	75.16	78.25

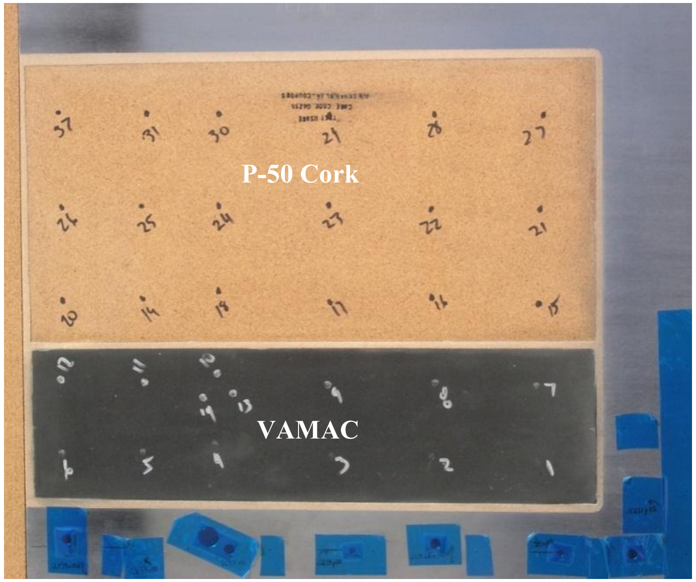
Centerline Heat Flux Comparisons (all methods)



Good agreement was achieved among analytical methods.

TPS Surface Point Measurements (Pre Test)





VAMAC Surface Survey Points			
Pretest			
Point ID #	X	Y	Z
1	29.559	18.836	-0.053
2	32.071	18.754	-0.054
3	34.493	18.769	-0.053
4	37.292	18.470	-0.053
5	39.088	18.655	-0.065
6	41.074	18.717	-0.071
7	29.577	17.003	-0.039
8	31.952	16.931	-0.035
9	34.548	16.972	-0.026
10	37.248	16.712	-0.031
11	39.008	16.944	-0.048
12	41.091	16.912	-0.065
13	36.812	17.179	-0.031
14	37.578	17.303	-0.035

P-50 Cork Surface Survey Points			
Pretest			
Point ID #	X	Y	Z
15	29.486	15.041	-0.020
16	32.038	14.877	-0.009
17	34.469	14.952	-0.002
18	37.187	14.716	-0.005
19	39.017	14.917	-0.023
20	40.990	14.937	-0.046
21	29.474	12.770	-0.018
22	32.049	12.726	-0.008
23	34.516	12.674	-0.004
24	37.146	12.681	-0.005
25	39.024	12.689	-0.019
26	40.999	12.738	-0.044
27	29.392	10.537	-0.019
28	31.983	10.529	-0.017
29	34.489	10.498	-0.017
30	37.152	10.483	-0.022
31	38.902	10.446	-0.035
32	41.085	10.422	-0.050

TPS Surface Point Measurements (Post Test)

Post Scrape - Char Layer Removed

VAMAC Surface Survey Points			
Post-Test with Char Removed			
Point ID #	X	Y	Z
1	29.559	18.836	-0.227
2	32.071	18.754	-0.246
3	34.493	18.769	-0.270
4	37.292	18.470	-0.304
5	39.088	18.655	-0.334
6	41.074	18.717	-0.362
7	29.577	17.003	-0.181
8	31.952	16.931	-0.191
9	34.548	16.972	-0.216
10	37.248	16.712	-0.245
11	39.008	16.944	-0.293
12	41.091	16.912	-0.335
13	36.812	17.179	-0.249
14	37.578	17.303	-0.275

P-50 Cork Surface Survey Points			
Post-Test with Char Removed			
Point ID #	X	Y	Z
15	29.486	15.041	-0.236
16	32.038	14.876	-0.261
17	34.469	14.952	-0.301
18	37.187	14.716	-0.332
19	39.017	14.917	-0.390
20	40.990	14.937	-0.448
21	29.474	12.770	-0.172
22	32.049	12.726	-0.185
23	34.516	12.674	-0.209
24	37.145	12.680	-0.255
25	39.024	12.689	-0.304
26	40.998	12.738	-0.348
27	29.392	10.537	-0.141
28	31.983	10.529	-0.153
29	34.489	10.498	-0.172
30	37.152	10.483	-0.206
31	38.902	10.445	-0.226
32	41.085	10.422	-0.268

Key Data Observations

- Instrument readings and video suggest that significant variations in both plume shape and motor thermal output occurred after T+3 seconds into the test. This event is still unexplained but good data exists prior to 3 seconds.
- Particle plume impingement was not expected to occur on the test article
  - **Heat flux measurements were inline with pre-test CFD heating**
  - **Significant Aluminum deposition was observed between Stations 30 to 36**
- The thermocouple array at Station 21 and post-test inspection of the panel (aluminum deposition and burn patterns) indicated that the plume centerline was an inch or more below the panel centerline, likely after T=3 seconds
- Initial data inspection appears to indicate that the best data for CFD comparison is prior to the peak transient event (T=1-3 seconds)
- The measured radiative heating was higher than expected and is being investigated
- Nearly all instrumentation survived the test, performed as expected and are reusable with standard refurbishment
- TPS sample recession was measurable and significant but less than predicted
  - Using Shuttle Heritage TPS Recession Rates

SRTMV-N2 PITP Data Analysis, Documentation, and CFD Code Validation Plans

PITP Data Analysis Plans

- Full spatial inspection and analysis of all streamwise and spanwise pressure and thermal test data from the PITP
  - Nearly Complete
- Analysis of all test data before and after the transient peak event for potential CFD comparison
  - Nearly Complete
- Examination of radiometer over-ranged data
  - Post-test calibration of radiometers is in progress and will be completed very soon
- Analysis of IR camera video data
- Analysis of temperature and erosion data from the VAMAC and P50 Cork TPS coupons (MPCV effort)

CFD Analysis Plans

Post-Test SRTMV-N2 Nozzle Test Conditions (SRTMV-N2 Funded):

- Post-Test Nozzle QA : COMPLETE
- Computation of Nozzle Geometry vs Test Time : COMPLETE
- Computation of Nozzle Test Conditions vs Time : COMPLETE

Post-Test CFD (MLAS Funded):

- Engineering Code Analysis of SRTMV-N2 Nozzle : COMPLETE
  - Nozzle exit conditions for CFD : COMPLETE
- Loci-CHEM CFD (Francisco Canabal, MSFC) : IN PROGRESS
- USM3D (Erik Tyler, LaRC) : IN PROGRESS

Post-Test CFD (MPCV Aerosciences Funded, Rick Thompson):

- VULCAN (Tom Jentink, LaRC)
- FUN3D (Victor Lessard, LaRC)
- Loci-CHEM (Alireza Mazaheri, LaRC)

SRTMV-N2 PITP Documentation Plans

- SRTMV-N2 PITP Test Report
  - PITP hardware, instrumentation, test conduct, and test data
  - A NASA/NESC archival document
- CFD Assessment for SRTMV-N2 PITP Test Data
  - An assessment of the multiple CFD codes and their results compared to the test data
  - A NASA/NESC archival document

Team Membership for PITP Risk Mitigation Task

Research Team Members	Responsibility
David Witte (LaRC)	FTV-2 Aero Lead / PITP PM
Jeremy Pinier (LaRC)	FTV-2 Deputy Aero Lead
Jason Mishtawy (MSFC)	Research Lead
Bud Smith (MSFC)	Aerothermal Loads
Vince Cuda (LaRC)	Thermal Analysis / Instrumentation
Francisco Canabal (MSFC)	CFD (Loci CHEM)
Erik Tyler (LaRC)	CFD (USM3D)
Tom Jentink (LaRC)	CFD (VULCAN)
Darrel Davis (MSFC)	TPS Research
Stan Bouslog (JSC)	TPS Research
Scott Coughlin (JSC)	TPS Research

Acknowledgments	Role
Jeremy Kenny (MSFC)	Guidance/Test Expertise
Sam Yunis(LaRC)	Structural Dynamics Support
Sandy Webb (LaRC)	Mechanical Design
Dave Castle (LaRC)	Mechanical Stress Analysis
Tom Hall (LaRC)	Instrumentation Installation Lead
Wayne Geouge (LaRC)	Instrumentation Installation
Rick Irby (LaRC)	Instrumentation Support Systems
Jeff Petty (LaRC)	Pressure Scanner DAS
Dennis Strickland (MSFC)	SPTA Facility Manager
Jason Elmore (MSFC)	SPTA Data Acquistion
Ernie Wooten (MSFC)	SPTA Instrumentation
Scott Ringel (MSFC)	SRTMV-N2 Design Lead
Darrell Gaddy (MSFC)	IR Cameras

Questions ?